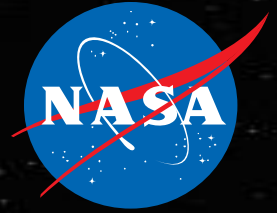


National Aeronautics and Space Administration
Marshall Space Flight Center



Reliability of Mechanical Behavior in Metallic Additively Manufactured Parts for Critical Applications

**Doug Wells
NASA MSFC
Huntsville AL**

**ASTM/NIST Workshop on
Mechanical Behavior in
Additive Manufactured parts**

May 4, 2016

There is more to AM than manufacturing

AM machines create a unique material product form – typically purview of the foundry or mill

Subtractive Forging Process



Additive SLM Process

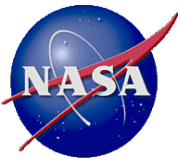


As the 'mill', the AM process must assure manufacturing compliance throughout the build process and material integrity throughout the volume of the final part.

- AM responsibility serving as the material mill gives rise to additional reliability concerns
 - Low entry cost compared to typical material producers
 - New players in AM, unfamiliar with the scope of AM, lacking experience
 - Fabrication shops not previously responsible for metallurgical processes
 - Research labs converting to production
- **AM machines operate with limited process feedback!**
 - Reliability depends upon the quality and care taken in every step of AM operations => rigorous and meticulous controls



Concept Laser X-line
Material Mill in a Box



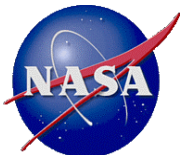
Opportunities to Secure AM Reliability



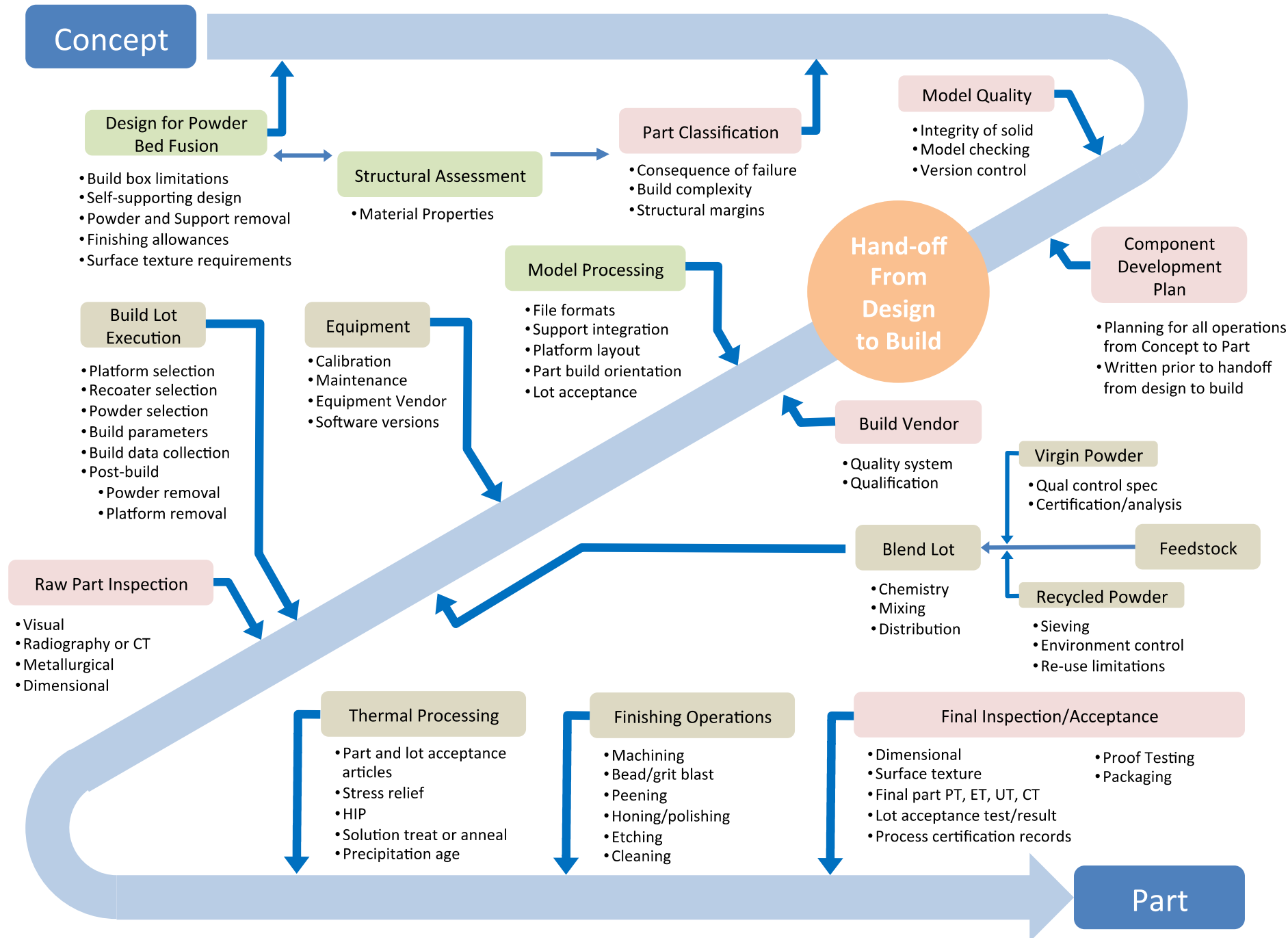
Two primary opportunities to ensure AM reliability

1. In-Process Controls, (Control what you do)
 - Understanding fundamentals of the process
 - Knowing the process failure modes (pFMEA)
 - Identifying observable metrics and witness capabilities
 - Meticulous process scrutiny
 - *Future to provide detailed process feedback for post-process evaluation or even closed-loop controls.*
2. Post-Process Evaluation (Evaluate what you get, NDE)
 - Extensive subject, ASTM E07 and many partners involved
 - Not covered in this discussion

Part reliability rationale comes from sum of both in-process and post-process controls, weakness in one must be compensated in the other

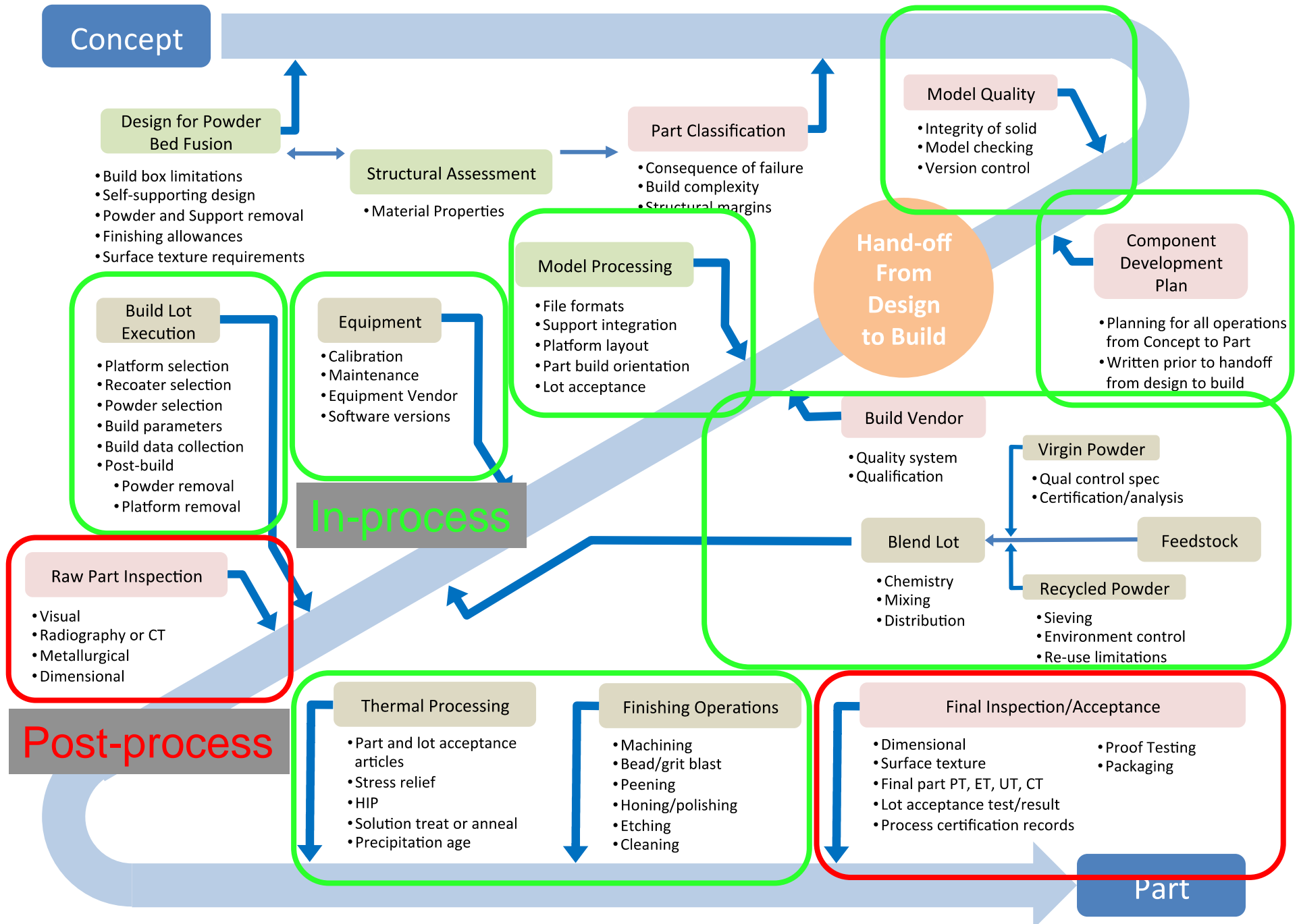


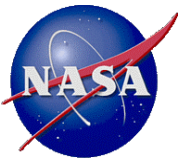
The AM Process: Concept to Part





The AM Process: Concept to Part





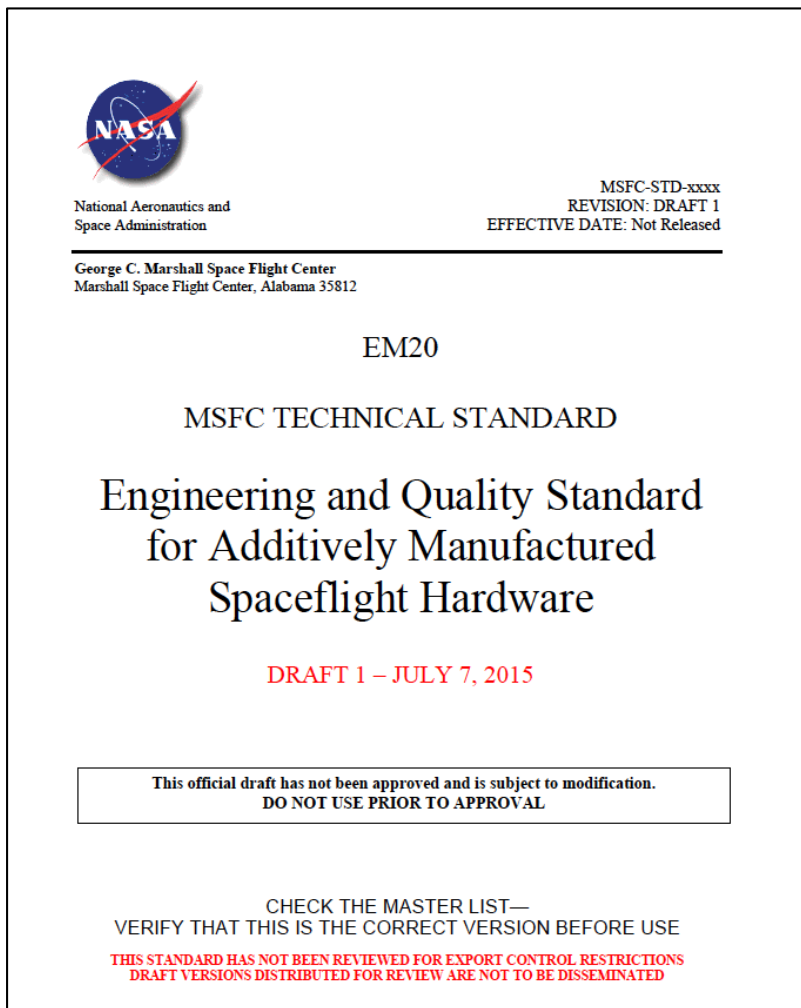
Standardization for AM Mechanical Reliability



- Systematic and controlled execution of AM processes is required to achieve requisite mechanical reliability
- Standardization of AM processes is actively pursued by private industry, government organizations, and standards development organizations worldwide.
 - ASTM F42, ISO collaboration
 - Only SDO with open, published AM standards
 - SAE AMS-AM
 - AWS
- NASA works with SDOs to bring open industry standards to AM
- **Currently available open industry standards do not levy sufficient controls for spaceflight applications**



Standardization for AM Mechanical Reliability



- Draft NASA MSFC Standard
- Current methodology for AM reliability for critical applications
 - Space Launch System
 - Commercial Crew Program



Aerojet Rocketdyne RS-25

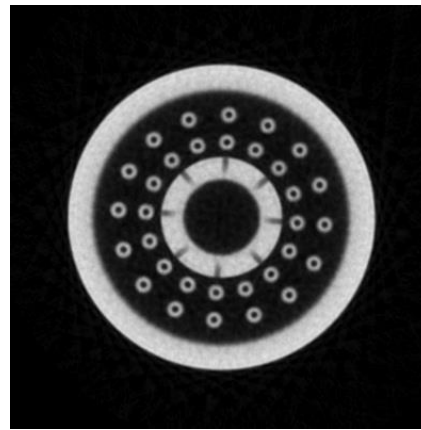


SpaceX SuperDraco

Draft NASA MSFC Standard implements four fundamental aspects of process control for AM:



Metallurgical
Process
Control



Part
Process
Control

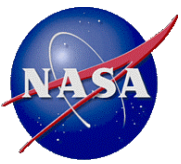


Equipment
Process
Control



Build Vendor
Process
Control

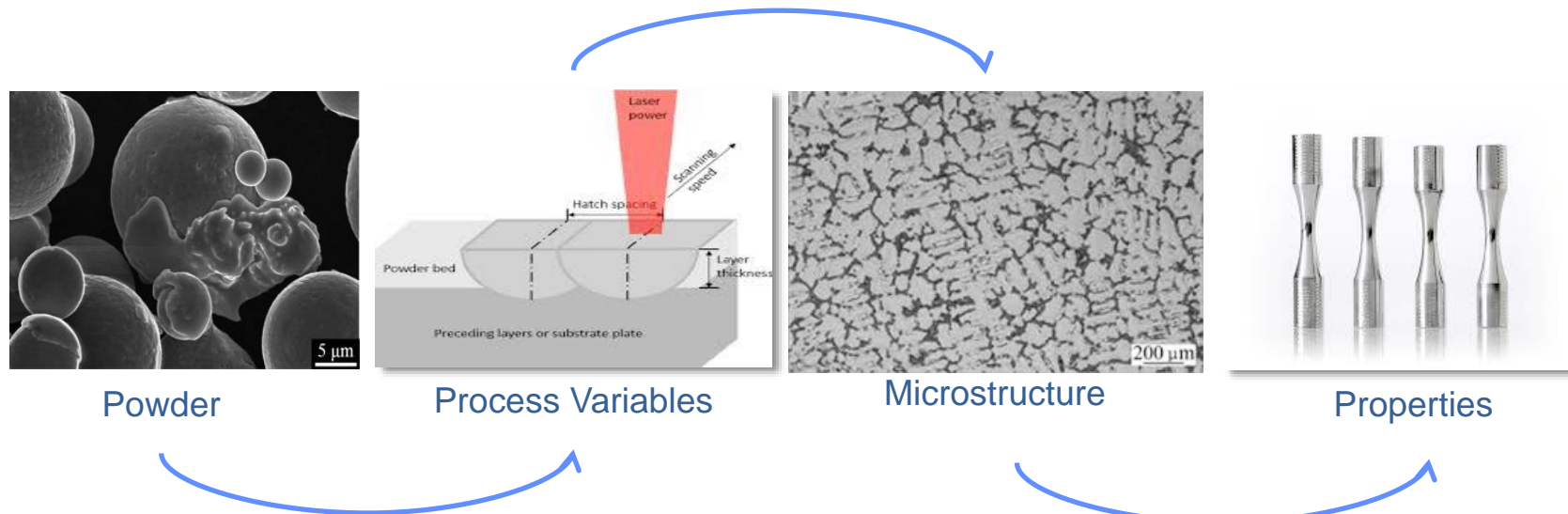
- Each aspect of process control is essential to the production of critical AM parts with reliable mechanical behavior
- Discussion here focuses on process control fundamentals for production of mechanically reliable AM materials



Foundation: Qualified Metallurgical Process



- Draft NASA MSFC Standard identifies AM as a unique material product form and requires the metallurgical process to be qualified on **every** individual AM machine
- While aspects of this foundation are present in, for example, ASTM F3055 (IN718 AM spec), rigor, qualification, and traceability are currently lacking.



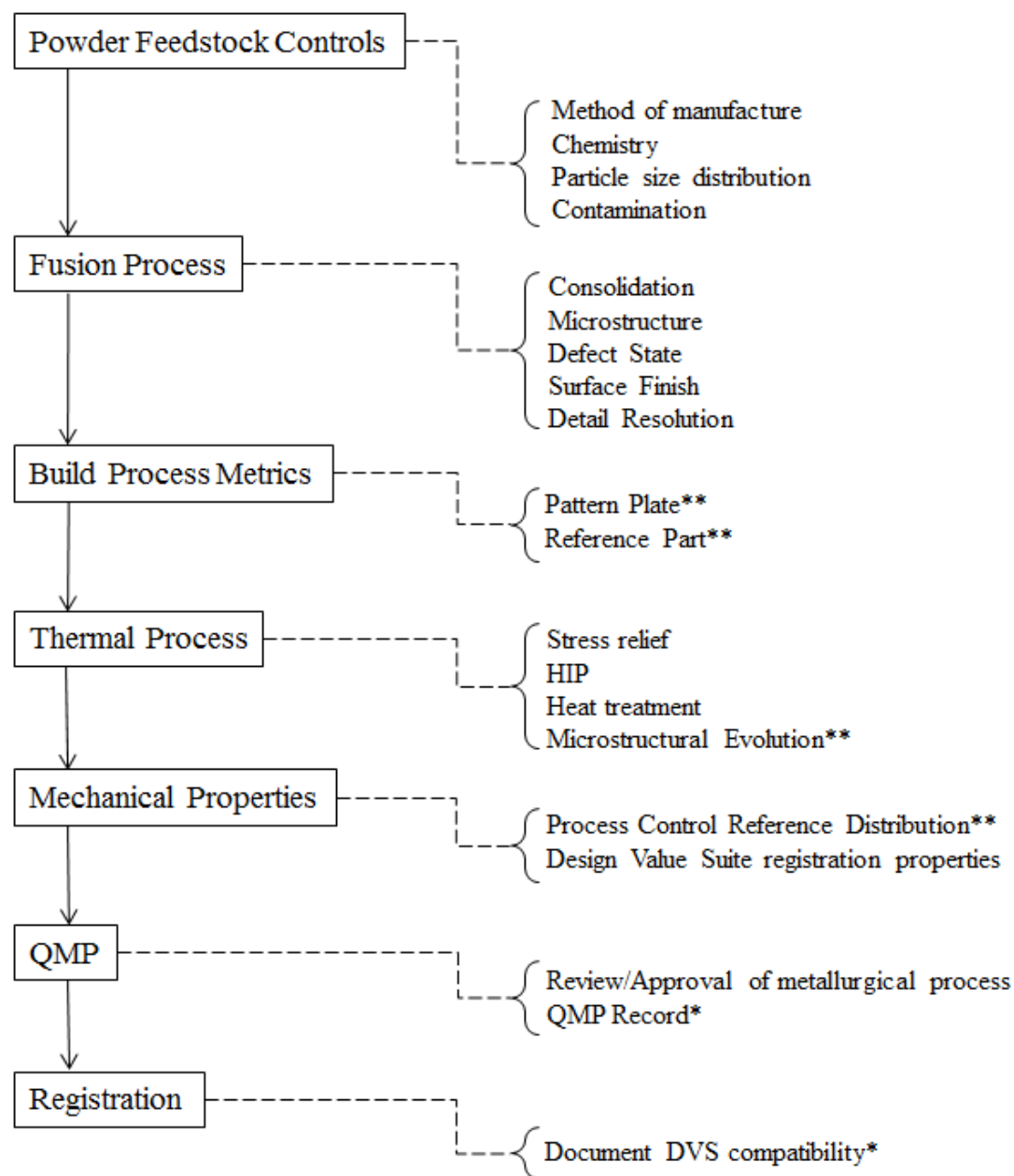


Foundation: Qualified Metallurgical Process



Qualified Metallurgical Process (QMP)

- Feedstock control or specification
- AM machine parameters, configuration, environment
- As-built densification, microstructure, and defect state
- Control of surface finish and detail rendering
- Thermal process for controlled microstructural evolution
- Mechanical behavior reference data
 - Strength, ductility, fatigue performance



*Quality management system record

**Acceptance criteria metric



As Built



Stress Relieved



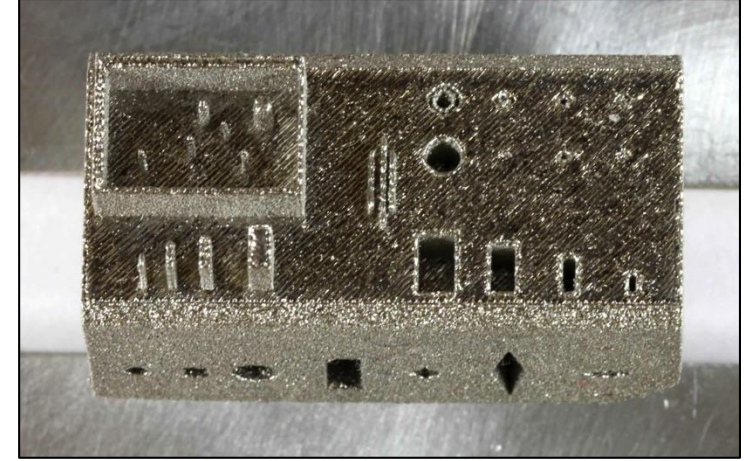
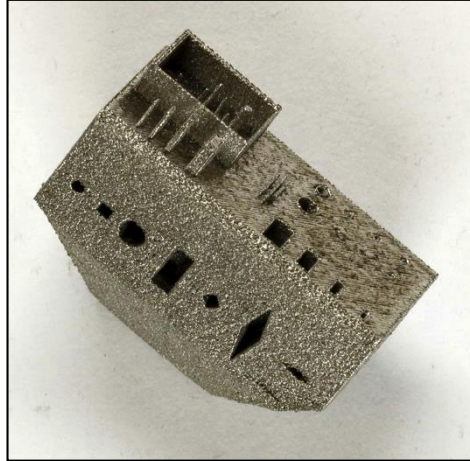
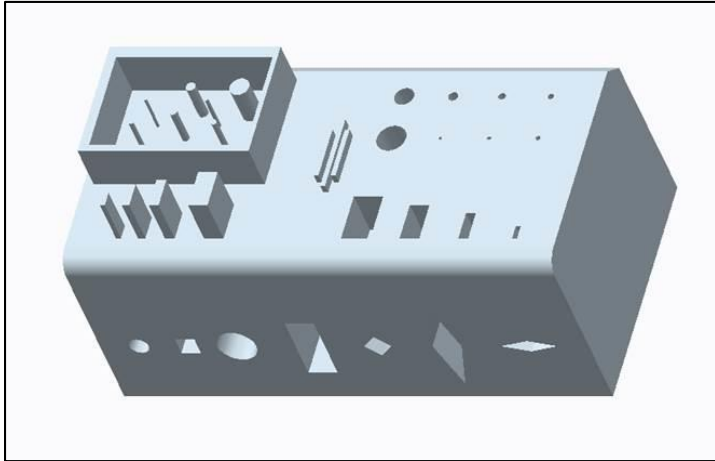
HIP & Final

Qualified Metallurgical Process (QMP)

- As-built densification, microstructure, and defect state
- Thermal process for controlled microstructural evolution



Foundation: Qualified Metallurgical Process



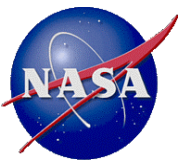
Reference parts:

Metrics for surface texture quality and detail rendering

Overhanging, vertical and horizontal surface texture, acuity of feature size and shape

Qualified Metallurgical Process (QMP)

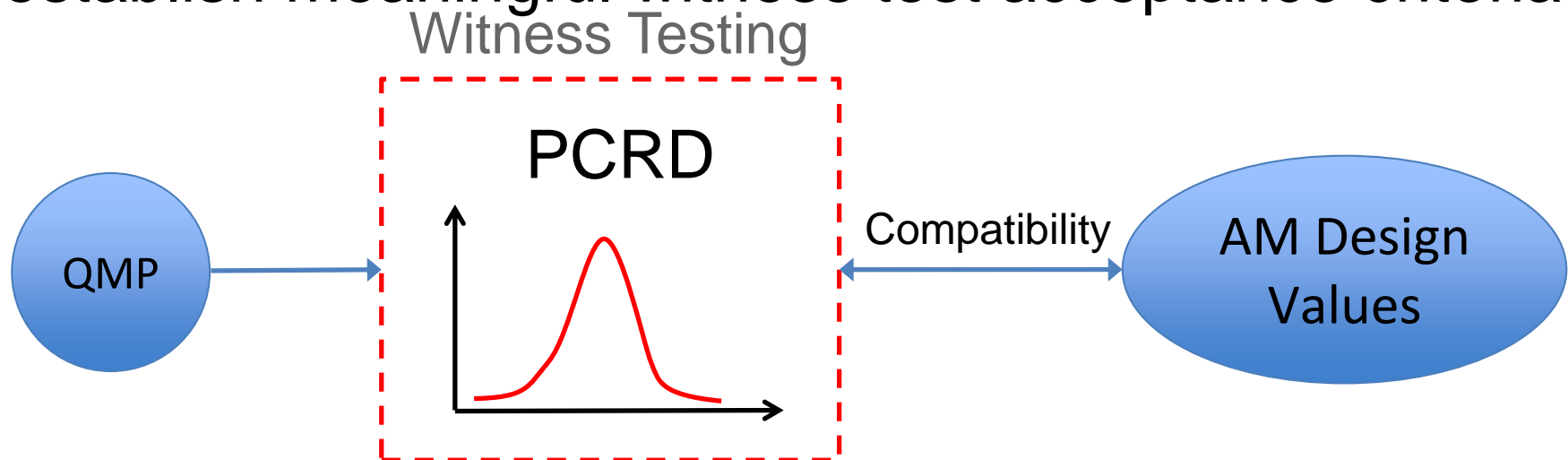
- Reference Parts
- Control of surface finish and detail rendering
- Critical for consistent fatigue performance if as-built surfaces remain in part

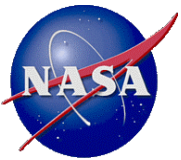


Foundation: Qualified Metallurgical Process



- Mechanical behavior reference data
 - Strength, ductility, fatigue performance
 - **Process Control Reference Distributions (PCRD)**
- Establish and document estimates of mean value and variation associated with mechanical performance of the AM process per the QMP
 - Will evolve with lot variability, etc.
- Utilize knowledge of process performance to establish meaningful witness test acceptance criteria





Foundation: Qualified Metallurgical Process



Types of AM build witness specimens

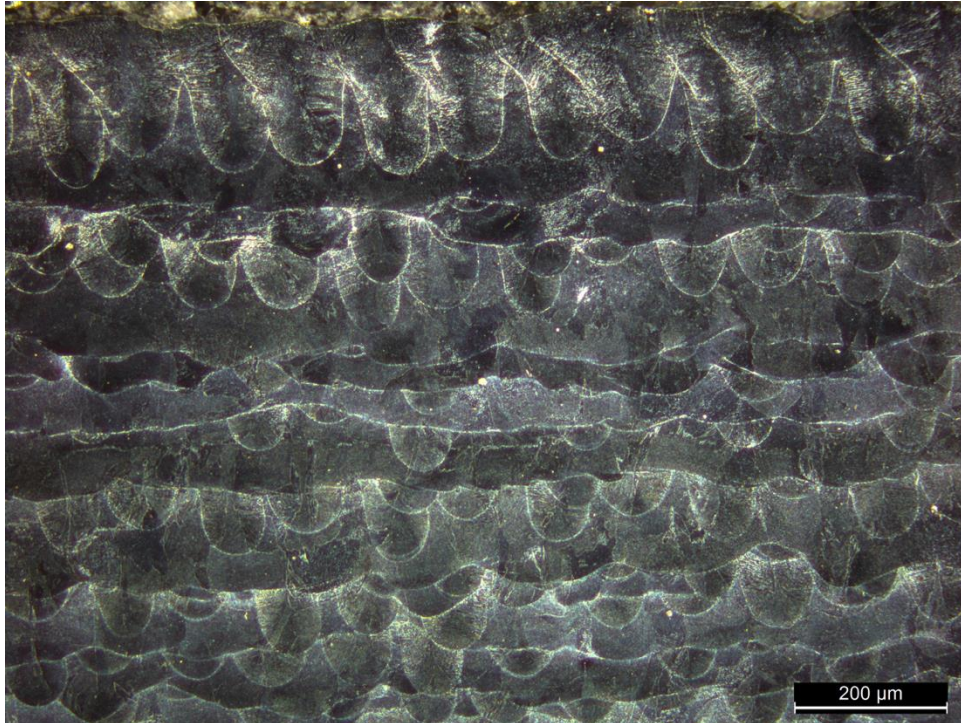
- Metallurgical
- Tensile (strengths and ductility)
- Fatigue
- Low-margin, governing properties

What is witnessed?

- Witness specimens provide direct evidence only for the systemic health of the AM process during the witnessed build
- Witness specimens are only an in-direct indicator of AM part quality through inference.

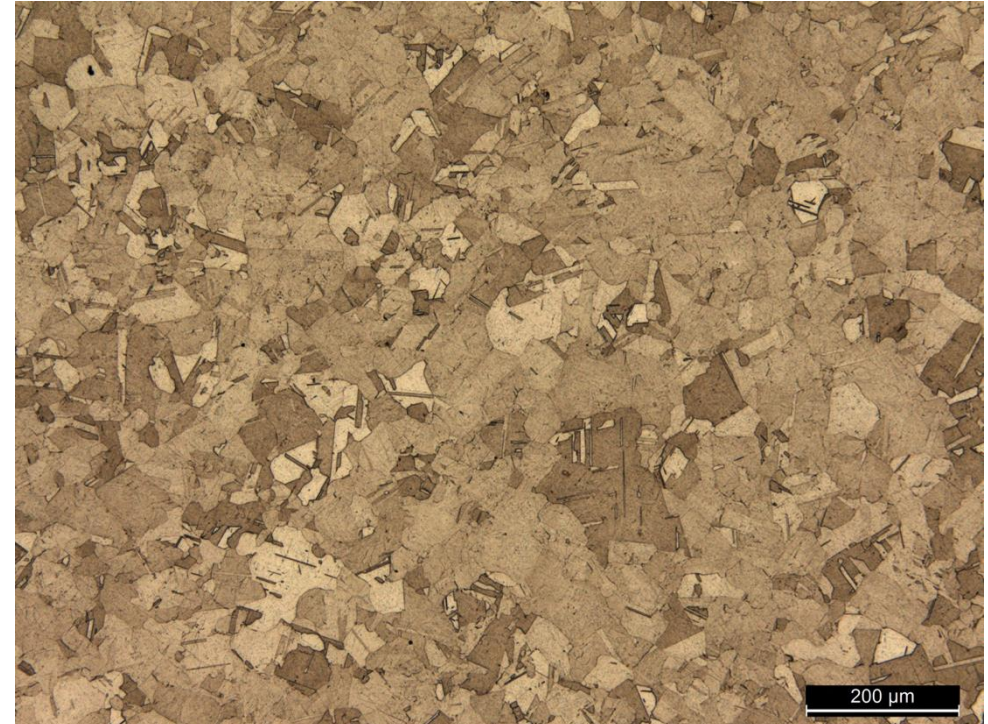
Types of AM build witness specimens

- Metallurgical



Example acceptance criteria - as-built state:

- Weld penetration depth and shape
- Grain nucleation patterns
- Porosity
- Lack of fusion / Cracks



Example acceptance criteria - final state:

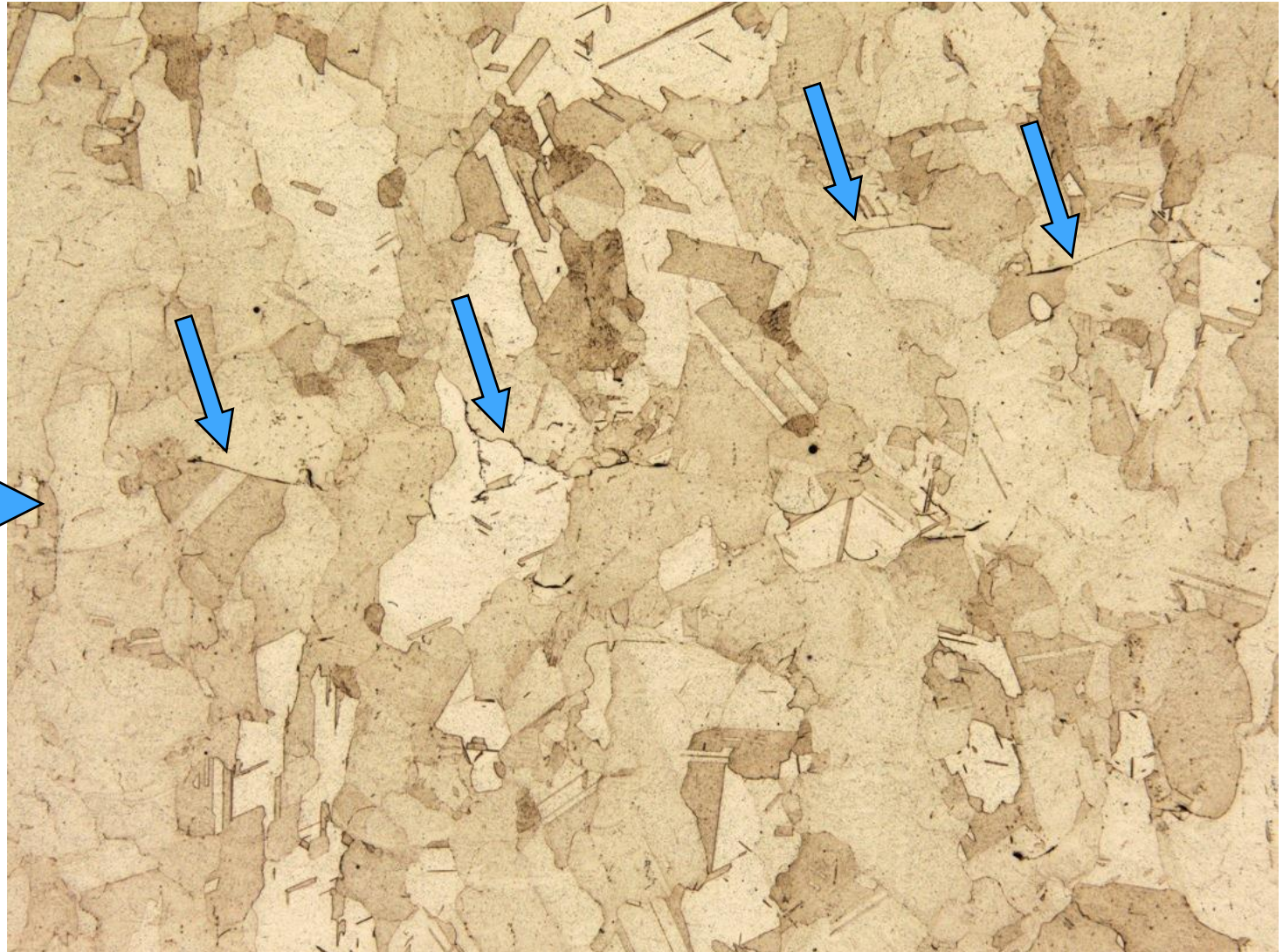
- Grain size
- Expected phases or carbide sizes
- Grain boundary cleanliness
- Porosity
- Lack of fusion / Cracks

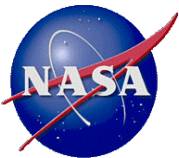
Types of AM build witness specimens

- Metallurgical

Example acceptance criteria - final state:

- Grain size
- Expected phases or carbide sizes
- Grain boundary cleanliness
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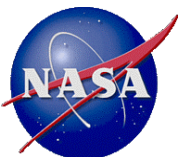


Types of AM build witness specimens

- Mechanical
 - Move away from spot testing with acceptance against 99/95 or specification minimums
 - Evaluate with sufficient tests to determine if the AM build is within family
 - Compromise with reasonable engineering assurance
 - Proposed
 - Six tensile
 - Two fatigue

Evaluate against the PCRCD of the QMP

- **Ongoing evaluation of material quality substantiates the design allowable**
- **Only plausible way to maintain design values**

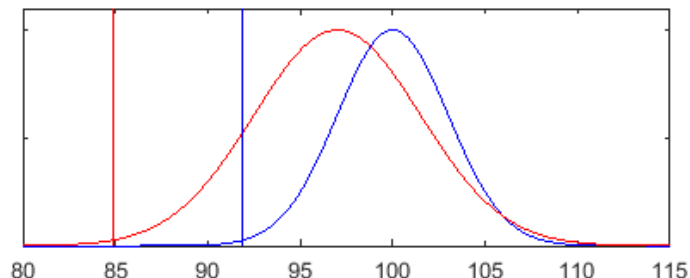


Witness for Statistical Process Control

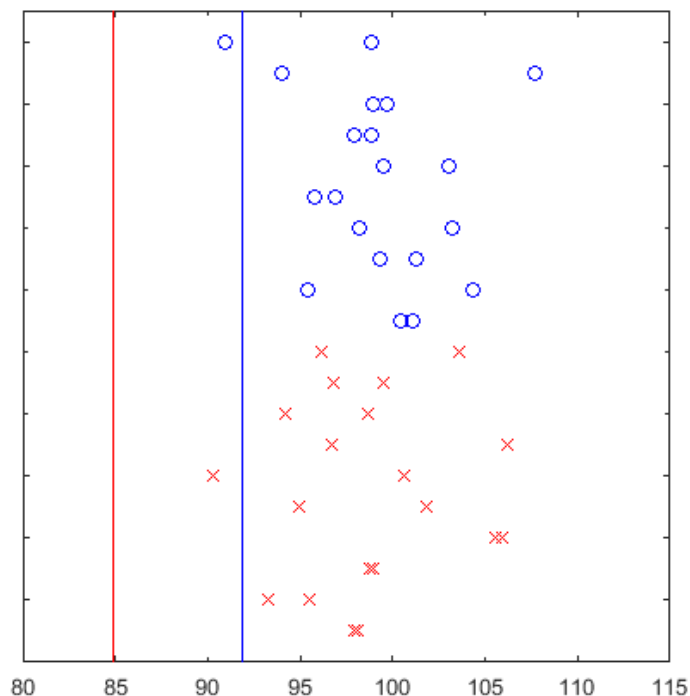


Example of AM build witness specimen evaluations

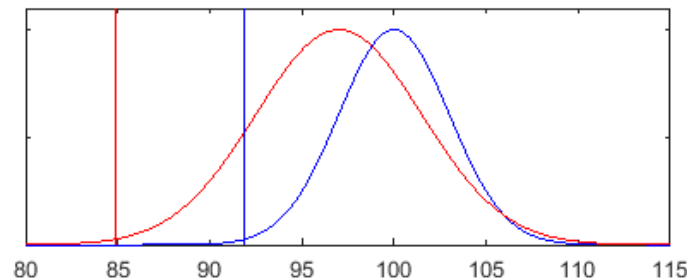
Nominal process is **blue**, off nominal in **red**



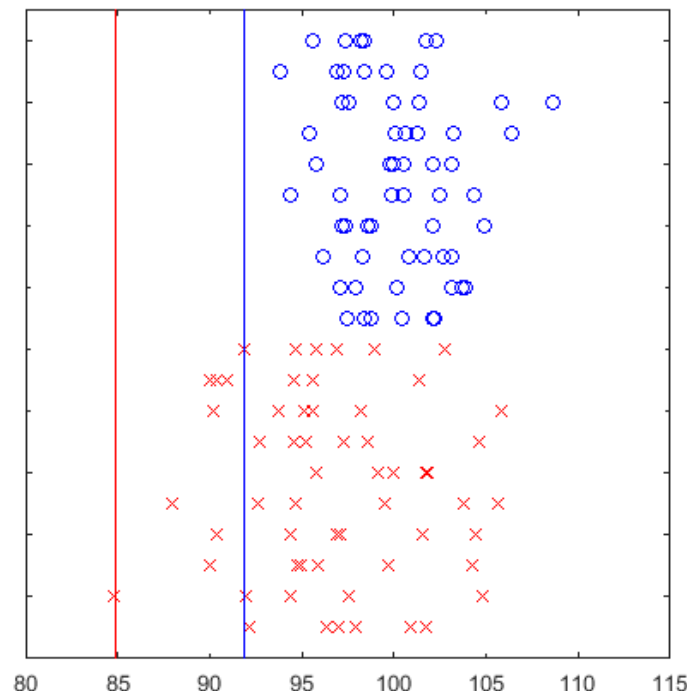
Two (2) witness tests per build



Process shift hard to discern



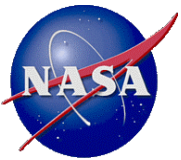
Six (6) witness tests per build



Process shift discernable with analysis of mean and variation

Random
draw from
nominal
process 10
times

Random
draw from
off-nominal
process, 10
times



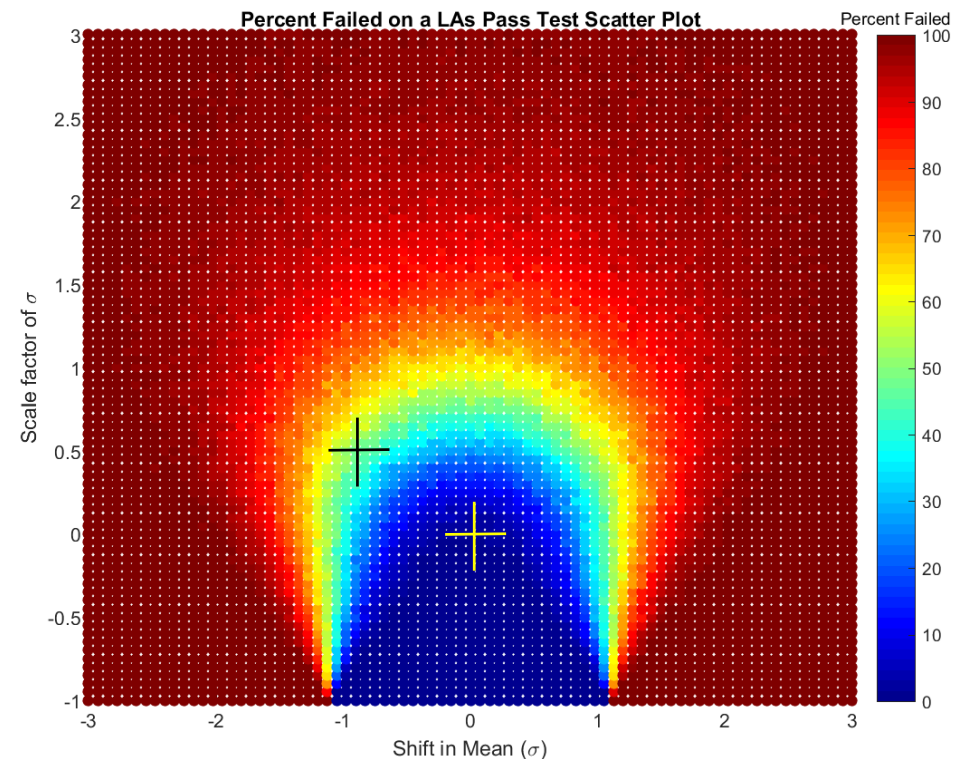
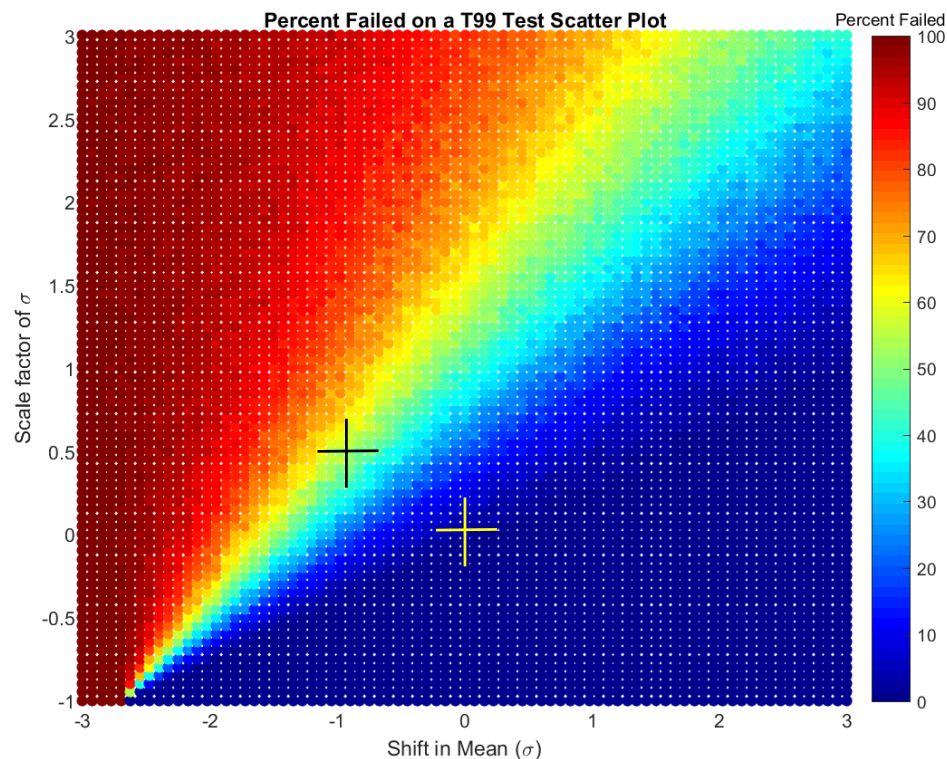
Witness for Statistical Process Control

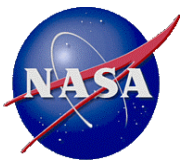


Simulation is used to evaluate small sample statistical methods for witness specimen acceptance

Design acceptance criteria for the following:

- Keep process in family
- Minimize false negative acceptance results
- Protect the design values witnessed
- Protect the inferred design values





Role of Quality Management System



AM process controls cannot be meaningfully implemented without oversight and integration with strong Quality Management System

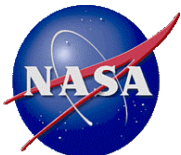
- Example, SAE AS9100

Mechanical reliability in AM cannot be established until:

- Process is defined and understood
 - Concept to Part
- Failure modes identified
- QMS engaged to monitor process and defeat failure modes



Standardization is key to developing a consistent approach

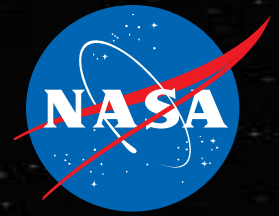


Summary of Points



To ensure mechanical reliability in AM:

- Requires thorough understanding and control of the process
 - Just as would be expected from a mill, foundry, or manufacturing house
- Requires sufficient process standardization to produce reliable parts in a routine fashion
- Requires quality management systems be in place
- Requires In-Process controls
 - Start with a solid foundation
 - Qualified metallurgical Process
 - Ensure mechanical reliability
 - Process witnessing, statistical evaluations
- Requires Post-Process controls
 - NDE
 - Proof testing
 - Etc.



Thank You

Additive Manufacturing at MSFC



